

Vacuum Application of Thermal Barrier Plasma Coatings

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ABSTRACT

Coatings are presently applied to Space Shuttle Main Engine (SSME) turbine blades for protection against the harsh environment realized in the engine during lift off-to-orbit. High performance nickel, chromium, aluminum and yttrium (NiCrAlY) alloy coatings, which are applied by atmospheric plasma spraying, crack and spall off because of the severe thermal shock experienced during start-up (-423°F to 1500°F) and shut down (1500°F to -423°F) of the engine. Ceramic coatings of yttria stabilized zirconia ($\text{ZrO}_2\cdot\text{Y}_2\text{O}_3$) were applied initially as a thermal barrier over coating to the NiCrAlY but were removed because of even greater spalling.

Utilizing a vacuum plasma spraying process, bond coatings of NiCrAlY have been applied in a low pressure atmosphere of argon/helium, producing significantly improved coating-to-blade bonding. The improved coatings showed no spalling after 40 MSFC burner rig thermal shock cycles, cycling between 1700°F and -423°F . The current atmospheric plasma NiCrAlY coatings spalled during 25 test cycles.

Subsequently, a process was developed for applying a durable thermal barrier coating of $\text{ZrO}_2\cdot\text{Y}_2\text{O}_3$ to the turbine blades of first stage high-pressure fuel turbopumps utilizing the vacuum plasma process. NiCrAlY bond coating was applied first, with $\text{ZrO}_2\cdot\text{Y}_2\text{O}_3$ added sequentially in increasing amounts until a thermal barrier coating of 50/50 NiCrAlY and $\text{ZrO}_2\cdot\text{Y}_2\text{O}_3$ was obtained. The improved thermal barrier coating has successfully passed 40 burner rig thermal shock cycles without spalling.

Hot firing in an SSME turbine engine is scheduled for the blades. Tooling has been installed in preparation for vacuum plasma spray coating other SSME hardware, eg. the titanium MFVH (main fuel valve housing) and the fuel turbopump nozzle/stator.

INTRODUCTION

The turbines in the High Pressure Fuel Turbopump (HPFTP) of the Space Shuttle Main Engine (SSME) experience a tremendous thermal shock in operation. The turbines are heated from cryogenic temperatures to operating temperatures of nearly 815°C in one second at engine start-up. After the turbine blades have been operating at 815°C and 34,700 RPM for the 500 seconds of flight operation, the turbines are quenched in liquid hydrogen at -253°C. The thermal shock induces high thermal strains on the surfaces of the turbine blades and nozzle/stator rings. In this investigation different Thermal Barrier Coatings, TBC's, were applied and tested on SSME HPFTP turbine blades. The TBC's are to be used to lower the thermal shock of the substrate materials thereby extending the life of the turbine blades and nozzle/stators.

PROCEDURE

TBC's were applied by Vacuum Plasma Spray, VPS, and Air Plasma Spray, APS, onto Mar-M-246 +Hf Turbine Blades and tested for adherence in a thermal shock tester. In addition the thermal conductivities of the coatings were measured, and the densities calculated.

The materials used for TBC's were:

Ni-16.5 Cr-5.5 Al-0.55Y

and

$\text{ZrO}_2\text{-}8\text{ Y}_2\text{O}_3$

and combinations of both materials.

The VPS coatings were applied in a Low Pressure Plasma Spray Unit at the NASA Marshall Space Flight Center. The APS coatings were applied by a SSME approved vendor, Plasma Coating Corporation.

RESULTS

Thermal Shock Adhesion

SSME HPFTP 1st Stage Mar-M-246+Hf turbine blades were tested in the MSFC Turbine Blade Thermal Shock Tester for coating adherence by thermal cycling from 870°C to -180°C. Test cycling has been described in earlier literature (1); the tester operates between environments of burning H₂ gas at 870°C and quenching liquid hydrogen at -252°C.

The coating adherence found is listed in Table 1. The APS coatings of NiCrAlY and NiCrAlY/ZrO₂ spalled randomly during testing; some coatings spalled after five (5) cycles where others produced in the same batch exhibited a life of twenty-five (25) cycles. This lack of repeatability is disturbing. The VPS coatings of NiCrAlY, NiCrAlY ZrO₂•8Y₂O₃ mixture, and NiCrAlY with APS ZrO₂•8Y₂O₃ topcoats showed no signs of spalling in the typical twenty-five (25) cycle testing, but APS zirconia topcoats did show signs of erosion.

These thermal shock tests demonstrated the large increase in coating adherence due to the VPS process as compared to APS. The attributes of VPS are an oxide free bond coating and coating/substrate interface, greater density and uniformity. These attributes are well described in the literature. (2-4)

Thermal Conductivity

Thermal conductivities of six coatings, 0.010 in. thick, were calculated from specific heat (Cp), density (d), and thermal diffusivity (α) measurements. The thermal conductivity (λ) was found by taking the product of the measurements according to:

$$\lambda = \alpha C_p d$$

The measurements were determined by:

- Cp - differential scanning calorimetry
- α - laser flash technique
- d - bulk density from geometry and mass

All thermophysical measurements were conducted at the Thermophysical Properties Research Laboratory at Purdue University. (5)

The thermal conductivities are plotted in Figure 1 in the temperature range of -200 to 1000°C. The thermal conductivities in descending order of conductivity are:

VPS	NiCrAlY
VPS	70% NiCrAlY/30% ZrO_2 8Y ₂ O ₃ (by volume)
APS	NiCrAlY
APS	70% NiCrAlY/30% ZrO_2 8Y ₂ O ₃ (by volume)
APS	ZrO_2 8Y ₂ O ₃

This data clearly shows that thermal conductivity is related the material properties and also the processing. The same NiCrAlY or NiCrAlY/ ZrO_2 8Y₂O₃ mixture applied by the two different processes gave different thermal conductivities as well as different thermal shock lives.

Density

The bulk densities of each coating are shown in Figure 2. It is quite evident that the thermal conductivity is also directly related to density of the material. With increased oxide and porosity content the density and thermal conductivity become lower.

DISCUSSION OF RESULTS

The thermal conductivity of Thermal Barrier Coatings has been found to directly relate to:

- coating application
- coating adhesion
- coating density
- material properties

and indirectly relate to:

- amount of oxide content
- porosity

The VPS coatings with higher thermal shock adhesion, and density had higher thermal conductivities. The APS coatings of the same materials were more porous and oxidized, and therefore had lower thermal conductivities.

The difference between APS and VPS coatings illustrates the tradeoffs encountered in the design of TBC's between thermal conductivity, density, and coating life. The more insulative coatings do not have the life of less insulative coatings.

With the flexibility of VPS, coatings can be tailor made for the application. Since the coating adherence problem has been overcome with the VPS process, more insulative coatings are now being developed. VPS coatings containing greater volumes of ceramics are being developed, and these are thought to increase the thermal dampening capability past those tested in this study.

CONCLUSION

The method of application of TBC's plays as major a role in the life and thermal conductivity of the coating as does the material properties. In order to increase the life of TBC's on the SSME Turbine Blades, the Vacuum Plasma Spray Process must be utilized. To keep equivalent thermal conductivity of APS coatings, increased ceramic, $\text{ZrO}_2 \cdot 8\text{Y}_2\text{O}_3$, content must be used in the VPS coatings. New coatings are being developed that go from thirty (30) volume percent ceramic to seventy (70) volume percent.

Insulative VPS TBC's have been found to adhere to the SSME turbine blades for over twenty-five (25) thermal shock cycles. Existing APS coatings spall after as few as five (5) cycles. The TBC's can increase the thermal low cycle fatigue life of SSME HPFTP turbine blades and nozzle/stators by affording thermal protection from severe thermal shock.

TABLE 1

THERMAL SHOCK CYCLIC TESTING

Between (870°C and -180°C)

<u>Bond Coating *</u>	<u>Thermal Barrier Coating (.004 in)</u>	<u>Number of Cycles</u>	<u>Comments</u>
VPS NiCrAlY	--	25+	No spalling
APS NiCrAlY	--	5-25+	Spalling
VPS NiCrAlY	VPS NiCrAlY/ZrO ₂ • 8Y ₂ O ₃	25+	No spalling
VPS NiCrAlY	APS ZrO ₂ • 8Y ₂ O ₃	25+	No spalling, erosion of porous ZrO ₂ 8Y ₂ O ₃
APS NiCrAlY	APS ZrO ₂ • 8Y ₂ O ₃	5-25+	Spalling

* Bond coating only: 0.006 in. thickness

Bond coating before adding thermal barrier coating: 0.002 in. thickness

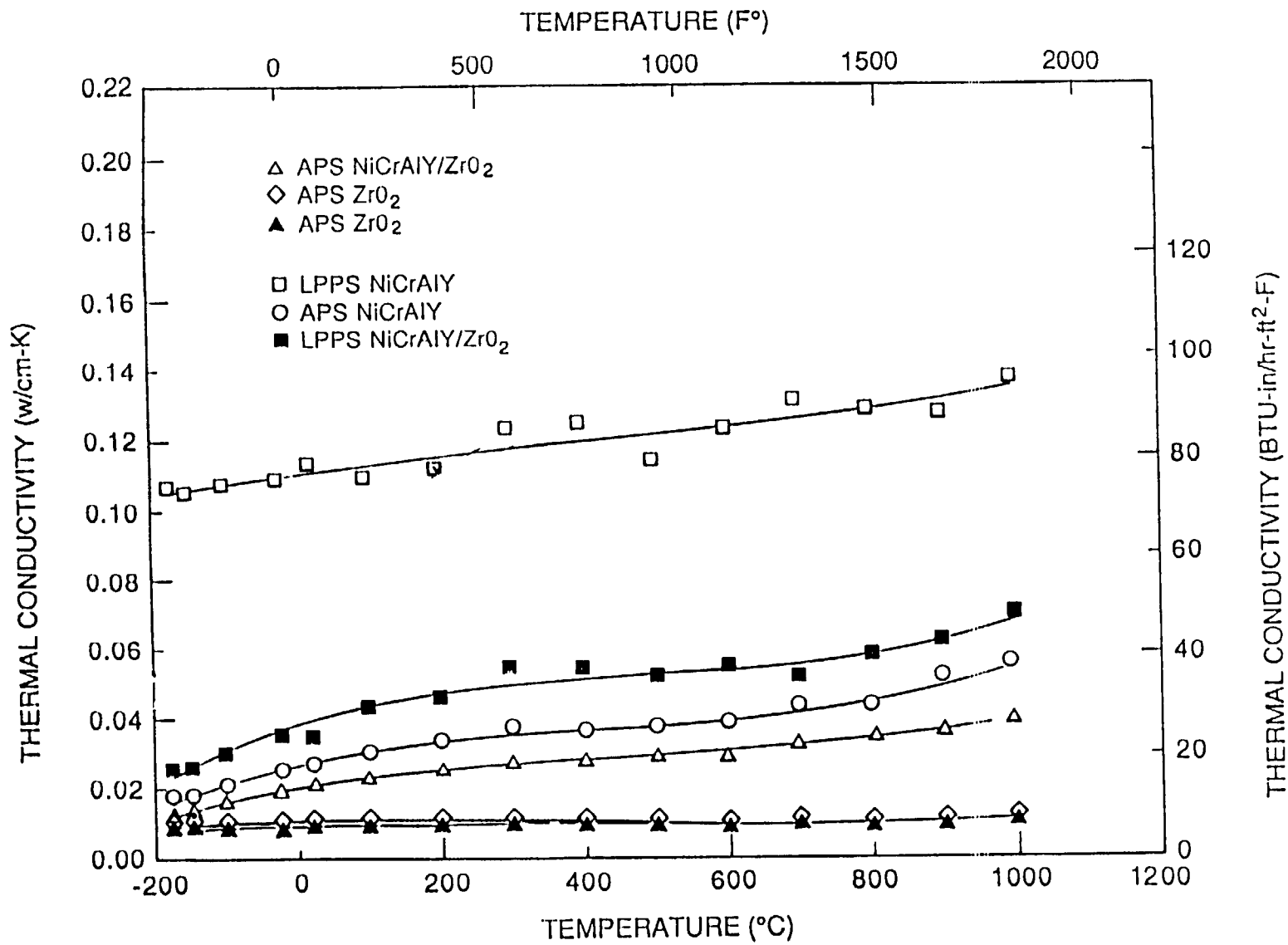
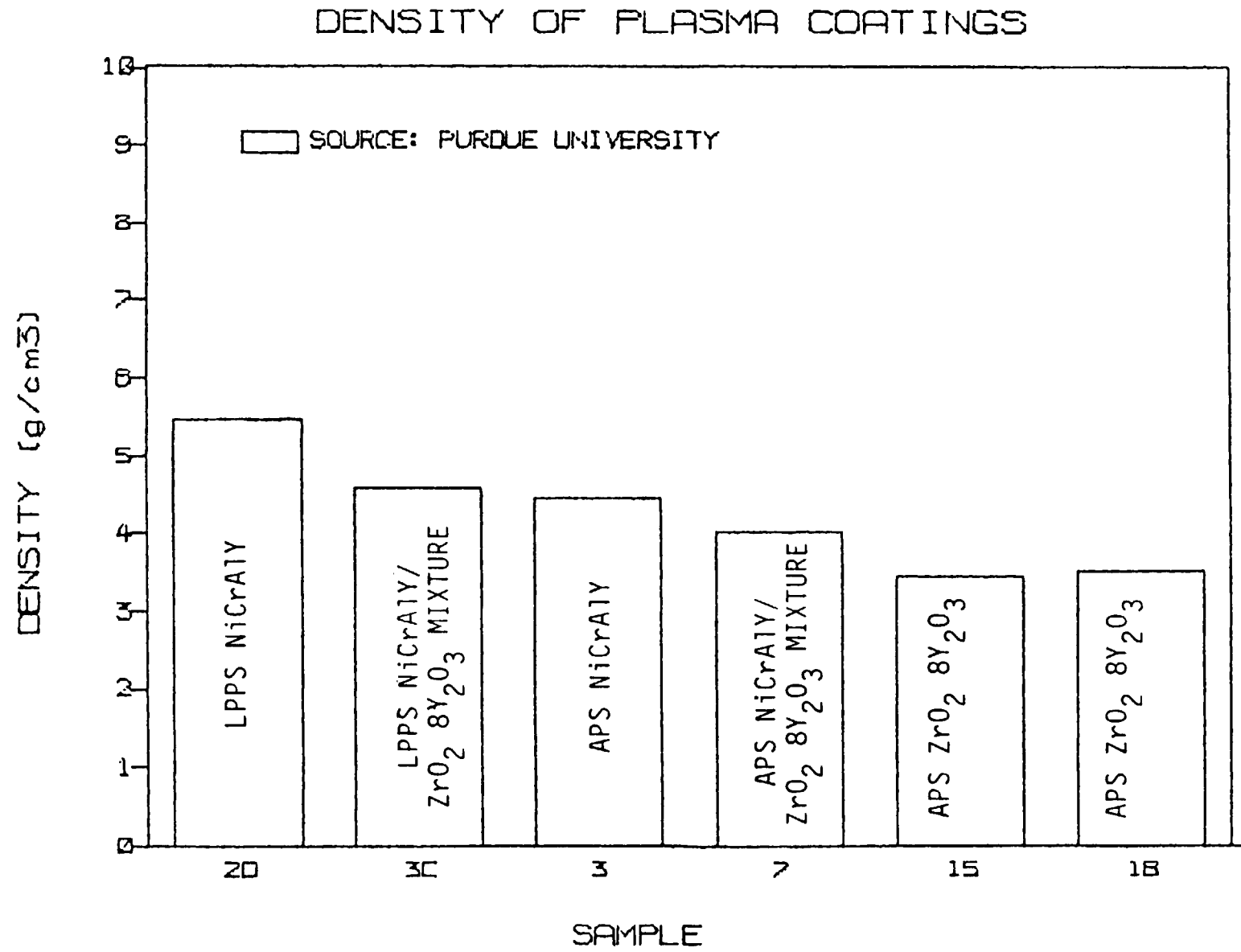


FIGURE 1. THERMAL CONDUCTIVITY OF COATINGS

FIGURE 2



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